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Optimal Angle Error Reduction of Magnetic Position Sensor by 3D Finite Element Method

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This paper deals with an optimal angle error reduction method of magnetic position sensor using hall effect elements. The angle detection simulation for the magnetic position sensor is performed by 3 dimensional finite element method and Taguchi method, one of the design of experiments. The magnetic position sensor is required to generate ideal sine and cosine waveforms from its hall effect elements according to rotation angle for precise angle information. However, the output signals are easy to include harmonics due to uneven magnetic field distribution from permanent magnet in the air-gap in the vicinity of hall effect elements. For the Taguchi method, three design parameters related to position of hall effect elements and shape of back yoke are selected. The characteristics of optimal magnetic position sensor are compared with those of original one in terms of simulation as well as experiment. Finally, the performances of the motor adopting original model and optimal model are represented for the purpose of verification of motor performance due to signals from magnetic position sensor.

Keywords : angle error reduction, magnetic position sensor, 3D finite element method, taguchi method

1. Introduction

Nowadays, permanent magnet motors are mainly used for an automobile application [1, 2]. They need appropriate position sensors in order to be controlled in accordance with position reference or speed reference by an inverter. Moreover, they need initial position information of permanent magnet rotor for instant control performance. Especially, in case of an interior permanent magnet synchronous motor (IPMSM) which is often used in automotive application, it should be operated by field weakening control requiring exact rotor position in order to make maximum torque [3, 4]. As position sensors for an absolute position angle, resolver and absolute encoder are generally used. However, they have several elements with complex structure as well as with high price. In case of absolute encoder, it is apt to be fragile due to external vibration. On the contrary, magnetic position sensor has simple structure of two stationary hall effect elements detecting magnetic flux and rotating multi pole permanent magnet generating magnetic flux [5].

In order to make precise position information, the magnetic position sensor should generate ideal sine and cosine waveforms from two hall effect elements which are apart from 90 degree electrically each other. However, the waveforms of magnetic position sensor usually have harmonics, 3rd harmonic in particular which is main source of position error because of uneven magnetic field distribution near the hall effect elements.

In the paper, an optimal design method considering error reduction of position information is proposed by using 3D FEM and Taguchi method which is one of effective design of experiment methods. For the accuracy of the proposed method, ANSYS Maxwell 3D FEM software is used. As controller give the wrong current reference into the IPMSM due to position error of magnetic position sensor, the torque performances of motor are simulated and experimented by adopting two magnetic position sensors with different position error.

2. Analysis Model

The magnetic position sensor has two separated components. Multi-pole permanent magnet of ferrite material magnetized in axial direction is attached into the shaft of motor. The number of magnetized poles of magnet position

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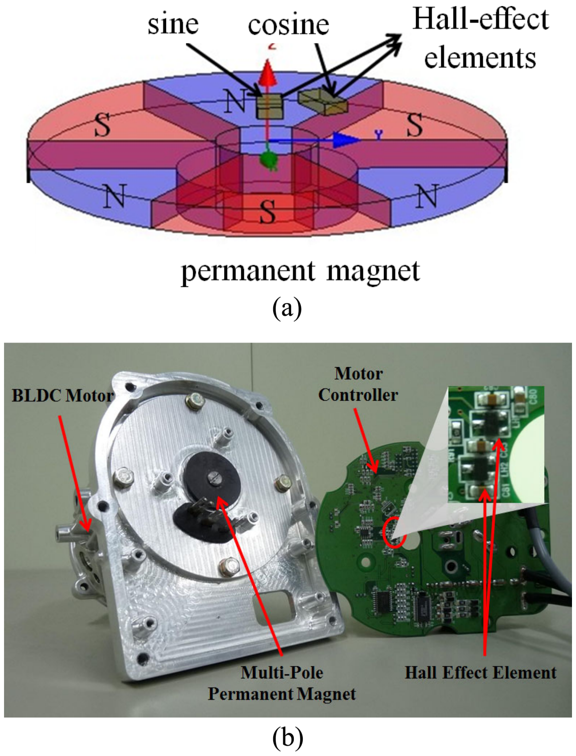

Fig. 1. (Color online) Analysis model and application of the magnetic position sensor. (a) 3D FEM analysis model for the magnetic position sensor. (b) IPMSM and controller having magnetic position sensor.

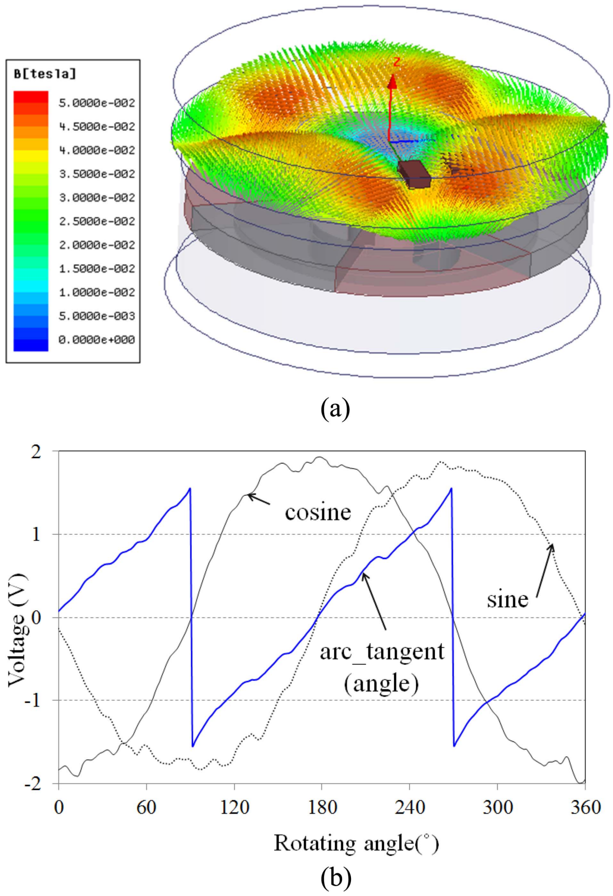

Fig. 2. (Color online) Analysis results of magnetic position sensor by 3D FEM. (a) Magnetic flux density distribution of magnetic position sensor by 3D FEM. (b) Analysis results of output signals and position angle information according to rotation angle.

sensor is equal to the number of poles of application motor. The two hall effect elements above the permanent magnet make sine and cosine waveforms due to magnetic flux from permanent magnet simultaneously because two hall effect elements are located 90° apart. Fig. 1 shows the analysis model of magnetic position sensor and an IPMSM with 6 poles as an application motor. It has a motor controller attaching two hall effect elements in the same housing.

Fig. 2 shows the analysis results of magnetic flux density distribution and output signal waveforms from hall effect elements by 3D FEM. For the 3D FE analysis, we use Maxwell software of ANSYS. The maximum flux density is about 0.012T in the vicinity of hall effect elements. The output signals of sine and cosine waveforms in Fig. 2 are derived from normal components of magnetic flux density when the permanent magnet rotates. The position angle can be calculated by arctangent function of sine and cosine waveforms in Eq. (1). Because of uneven magnetic flux density in the vicinity of hall effect element, the sine and cosine waveforms are distorted by 9.87% which value corresponds to total harmonic distortion (THD) in Eq. (2).

$$THD = \frac{V_H}{V_1} = \frac{\sqrt{V^2 - V_1^2}}{V_1} = \frac{\sqrt{\sum_{n \neq 1} V_n^2}}{V_1} \tag{1}$$

$$\theta = \tan^{-1}\left(\frac{\sin\theta}{\cos\theta}\right) \tag{2}$$

3. Optimal Angle Error Reduction

3.1. Methodology by Taguchi method

Taguchi method provides engineers with efficient method for determination of optimal set. It is kind of design of experiment (DOE) that uses orthogonal arrays for parameters analysis [6]. There are four steps for optimal angle error reduction using Taguchi method.

1) Identify design variables, noise factor, and objective function.

2) Identify levels of design variables.

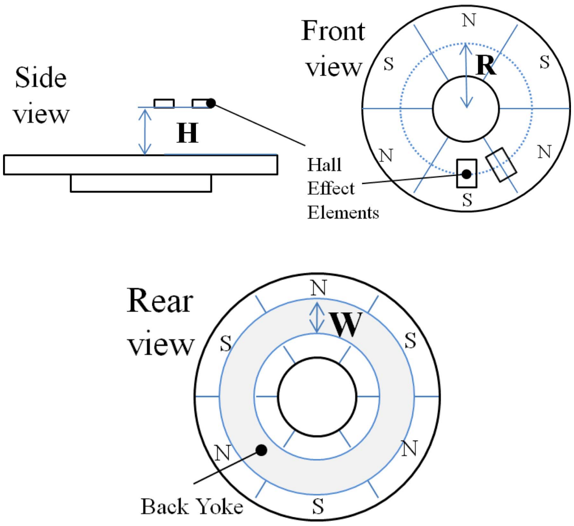

Fig. 3. (Color online) Three design parameters for Taguchi method (H, R, and W).

3) Define orthogonal array for Taguchi design.

4) Simulation the matrix experiment by FEM and ma-in effect analysis for the optimal results.

In the paper, three design variables related to distortion of output signal waveforms as shown in Fig. 3 are selected. Parameter H is clearance between permanent magnet and hall effect elements. Parameter R is radius from center of permanent magnet to position of hall effect elements. Parameter W corresponds to width of back yoke making higher magnitude of magnetic flux density. The center position of W is equal to R. The THDs of cosine and sine waveforms are slightly different due to FEM analysis error caused by tetrahedron mesh. Therefore these different values are selected as a noise factor. The objective function corresponds to minimum THD in its sine and cosine output signals.

Each design variables has three levels. Orthogonal array L9 is suitable in case of Taguchi's approach with above conditions. Matrix analysis results by FEM according to each objective function are shown in Table 1. In order to main effect analysis, signal-to-noise (SN) ratio representing smaller-the-better characteristic of THDs of output signals is used in Eq. (3).

Table 1. Matrix Analysis Results according to Orthogonal Array and noise factor.

Experiment	H (mm)	R (mm)	W (mm)	Sine (THD%)	Cosine (THD%)
1	4.0	8	2.5	3.558	2.298
2	4.0	8.75	3.5	3.781	3.512
3	4.0	9.5	5	4.169	6.908
4	4.8	8	3.5	3.269	2.255
5	4.8	8.75	5	4.094	3.678
6	4.8	9.5	2.5	4.694	2.352
7	5.5	8	5	3.191	1.147
8	5.5	8.75	2.5	3.294	1.646
9	5.5	9.5	3.5	3.265	1.784

$$SN = -10\log_{10}\sum_{i=1}^{n}\frac{y_i^2}{n} \tag{3}$$

Where n is the number of the experiment and y_i is the value of the experiment result.

As a result of position angle error reduction analysis, Fig. 4 shows the main effect plot for SN ratio. Optimal model has design variables of H = 5.5 mm, R = 8 mm, and W = 3.5 mm.

3.2. Comparison on the Angle Error by Simulation

The optimal model from Taguchi method should have minimum THD. In other words, the output signal waveforms of sine and cosine are almost similar to sinusoidal waveform. In order to show the reduction effect of position angle error, we compared the characteristics of optimal model with the original model already represented in Section 2. There is no back yoke component in the original model. The parameters and 3D FEM analysis results of THD are showed in Table 2, respectively. In an optimal model, there is improvement in position angle error about 68%-88%.

Figure 5 shows the output signal waveforms and position angle information between original model and optimal one. Optimal model has low voltage level in its signals,

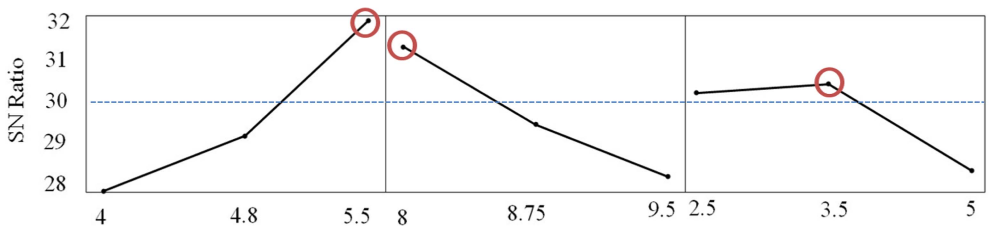

Fig. 4. (Color online) Main effect analysis on the SN ratio.

Table 2. Comparison Result between the Original Model and Optimal One (by Simulation).

	Original Model	Optimal Model
H (mm)	4	5.5
R (mm)	11	8
W (mm)	non	3.5
THD of sine (%)	7.72	0.91
THD of cosine (%)	9.89	3.16

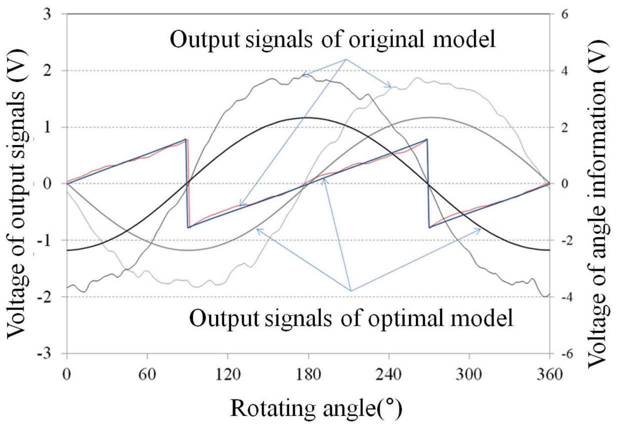

Fig. 5. (Color online) Output signal waveforms of sine and cosine and position angle information between original model and optimal one (by Simulation).

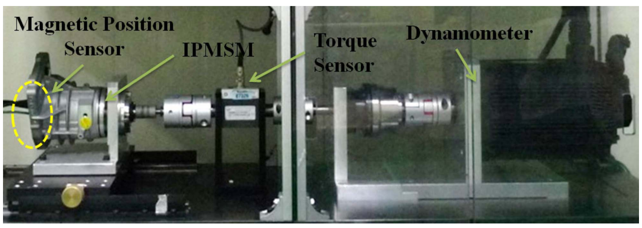

Fig. 6. (Color online) Experimental set for detection of rotation angle of magnetic position sensor.

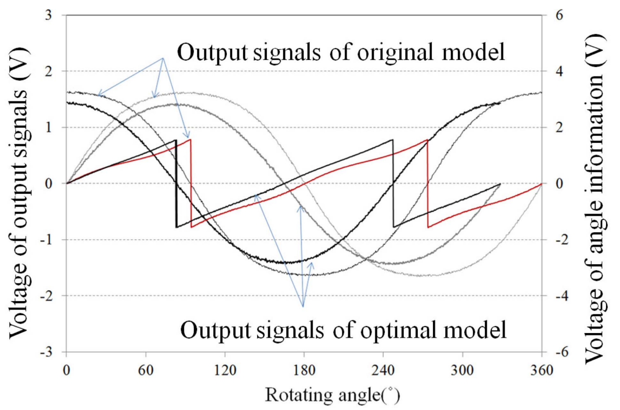

Fig. 7. (Color online) Output signal waveforms of sine and cosine and position angle information between original model and optimal one (by Experiment).

but it has linear position angle information.

3.3. Comparison on the Angle Error by Experiment

Two types of magnetic position sensor are produced in order to compare the characteristic exactly. Fig. 6 shows the experimental set for detection of several kinds of signal rated to rotating angle. The dynamometer should rotate its rotor with constant speed. The sine and cosine output waveforms and rotation angle information by experiment are shown in Fig. 7. Compared with simulation results, THD and position error by experiment are almost the same as simulation one. The position angle error are improved about 61%.

4. Characteristic Analysis of Motor Considering Angle Error

Optimal Model of magnetic position sensor has 2.7° position error which is remarkable reduced value compared with original one, 8°.

In order to control an IPMSM, it usually uses vector inverter which changes current angle meaning the angle between total current axis and q-axis current. At this point, the exact rotating angle of rotor is needed to convert d-axis and q-axis currents to three phase currents. Moreover, for the field weakening control, its current angle should be changed according to motor speed. It is difficult to show the precise experimental results on torque characteristic including ripples because of limitation of measure precision. Therefore, we analyze the effect on motor characteristics according to magnitude of position angle error by 2D FEM in the paper.

Figure 8 shows the analysis model of 6 poles IPMSM for motor driven power steering system (MDPS). It should be designed and controlled with low torque ripple. Due to

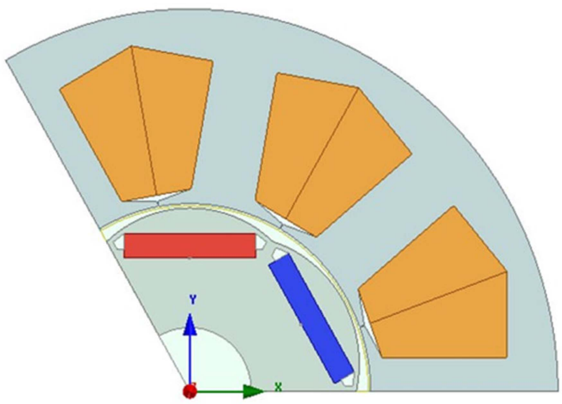

Fig. 8. (Color online) Analysis model of IPMSM with 6 poles.

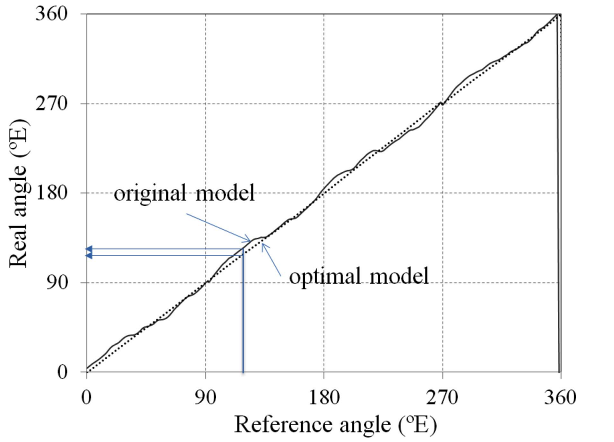

Fig. 9. (Color online) Position angle error according to rotating angle.

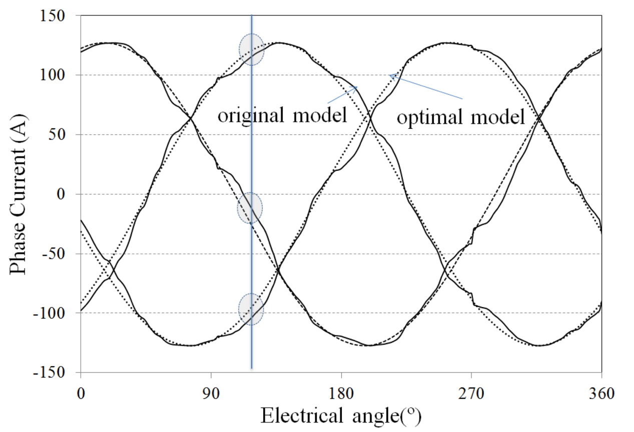

Fig. 10. (Color online) Three phase current waveforms of IPMSM with different magnetic position sensor due to wrong rotating angle information.

the position angle error according to rotation angle as shown in Fig. 9, the three phase current waveforms are distorted like Fig. 10 because of wrong angle information in the vector inverter.

The analysis result of torque characteristics by inputting these current waveforms according to rotating angle is shown in Fig. 11. The remarkable position angle error of magnetic position sensor affects torque characteristics directly as shown in Table 4.

5. Conclusion

The magnetic position sensor has the simplest structure in the angle sensors. However, it has remarkable position angle error and it is apt to be affected by external magnetic noise. In the paper, the novel design having improved angle error is proposed by using Taguchi method and 3D FEM. Moreover, in order to analyze the effect on angle error in a motor, the IPMSM adopting original and optimal magnetic position sensors is simulated by FEM. The position angle error directly affects the torque characteristics of the motor. The magnetic position sensor is easily influenced by external magnetic flux. Therefore, the magnetic shield structure of magnetic position sensor will be studied in the future.

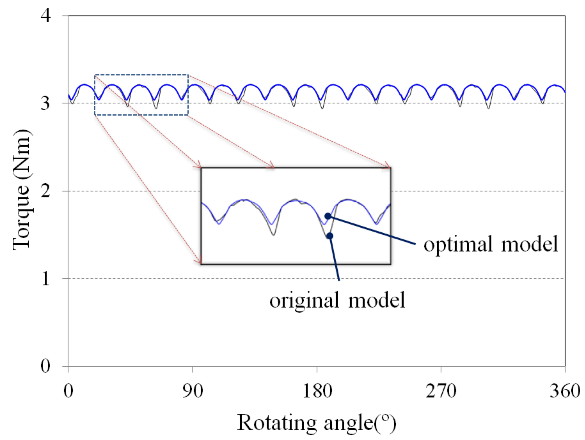

Fig. 11. (Color online) Analysis results of torque characteristics due to different magnetic position sensors.

Table 3. Comparison Result between the Original Model and Optimal One (by Experiment).

	Original Model	Optimal Model
THD of sine (%)	8.50	3.31
THD of cosine (%)	8.61	3.41
Position error (°E)	8	2.7

Table 4. Comparison Result between the Original Model and Optimal One (by Simulation).

	Original Model	Optimal Model	Remark
Average torque (Nm)	3.1416	3.1545	0.5% increase
Torque ripple (Nm)	0.2835	0.1758	40% decrease

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